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PRECAUTIONS FOR FLIGHT TESTING NEAR THE SPEED OF SOUND

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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Mr. Clousing's report summarizes the experience of the Committee's flight test staff in conducting research flights at high speeds, and contains information which will be of interest to all concerned in flight testing near sonic Mach numbers. The NACA believes that you will find it particularly desirable to bring the report to the attention of any test pilots or flight test personnel which may be a part of your organization.

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SUMMARY

From experience gained by NACA test pilots in flying at high subsonic Mach numbers and from interpretation of the data obtained, some general precautionary rules for test flying near sonic Mach numbers have been formulated. The reasons for these rules are discussed and observations are made with respect to the hazards arising from undesirable stability and control characteristics which have been noted in test flights of various airplanes.

This paper, although written primarily for the attention of test pilots, contains general information of interest to those who are concerned with various phases of flight testing near sonic Mach numbers. It includes a check list for use in organizing and summarizing pertinent information relative to the stability and control characteristics of airplanes undergoing tests at high Mach numbers.

INTRODUCTION

It is an indication of the progress made by aviation that there are increasing numbers of test pilots now being confronted with the special problems of flight testing near sonic Mach numbers. In this special realm of study, the NACA has acquired a good many years of experience with a variety of high-speed airplanes. Out of this experience have come certain general rules of action and precautions which have proven of such sound value that they should be useful to all engaged in conducting high-speed flights. And in this work, safety has more than its usual significance; it means not only the safe return of the pilot and airplane but also the acquisition of the knowledge which was the aim of the project. It is the purpose of this report to present a technique for the safe conduct of flight tests at high Mach numbers. Examples of troubles encountered with a discussion of their significance are included.

GENERAL PRECAUTIONARY RULES

Based on flight-test experience it has been demonstrated that several precautionary rules can greatly increase the safety of flight tests near sonic speeds. These rules will be presented in turn, and the reasons why the rules are considered advisable will be discussed.

Rule 1: All initial flight tests near sonic Mach numbers should be carried out at an altitude at which excessive air loads cannot result even though the airplane is stalled.- Adherence to this rule is advisable because experience has demonstrated that near sonic Mach numbers inadvertent pitching and even stalling of an airplane may occur. As examples of flight experience in this regard, figures 1 and 2 are presented. Figure 1, as discussed in reference 1, indicates the motions of a fighter airplane which occurred during a dive recovery at a high Mach number. It will be seen that during a normal recovery the airplane abruptly pitched up (at 7.5 seconds on the time history shown) even though the pilot had exerted no corresponding change in control force. The fact that the airplane was being tested at 27,000 feet prevented excessive air loads from resulting.

Figure 2 illustrates a case in which an unanticipated longitudinal oscillation of considerable intensity started while a fighter airplane was in a straight steady dive during flight tests by the NACA. Due to the unexpected occurrence of the oscillation, the recording instruments were not started in time to record the initial portion of the oscillation.

The effect of altitude on the load factor, that it is possible to impose, is shown in figure 3, for an airplane having a wing loading of 50 pounds per square foot and the variation of maximum lift coefficient with Mach number shown in figure 4. Figure 3 shows, as an example, that at a Mach number of 0.84 a load factor of about 19 is aerodynamically possible at sea level, although only about a load factor of 6 is possible at 27,000 feet.

The variation of maximum lift coefficient with Mach number, shown in figure 4, is believed to be typical for essentially unswept wings having modern airfoil sections of the subsonic type (rounded leading edges). In the lower Mach number range the curve was established from data presented in reference 2. The curve was extended to higher Mach numbers using a value of lift coefficient at full scale given in reference 1 and a value measured on an airplane model of very small scale at the Ames Laboratory by the wing-flow method. It will be noticed that a line describing a buffet boundary is included. This boundary, which also is believed to be typical for essentially unswept wings of modern airfoil sections of the subsonic type, was established using reference 2 and additional data from flight tests of a number of airplanes. Its significance in relation to maneuvering and structural strength will be discussed later.

Figure 3 can be employed to estimate the minimum altitude at which the allowable load factor of an airplane cannot be exceeded. If it is assumed that figure 4 represents the variation of maximum lift coefficient with Mach number, then it is only necessary to multiply the ordinate values of figure 3 by the factor

$$\frac{\text{Actual weight}}{\text{Rated weight}} \times \frac{50}{\text{Rated wing loading}}$$

in which the rated weight is the weight on which the allowable load factor is based. The acceleration factor a pilot would experience is the load factor from figure 3 multiplied by

$$\frac{50 \text{ (wing area in square feet)}}{\text{weight as flown}}$$

<u>Rule 2: At Mach numbers above the critical of the wing, flight tests at progressively higher values of Mach number should be undertaken only in small increments and only after exploring accelerated flight characteristics at lower Mach numbers.</u>- The general reasoning behind this rule should be apparent. The situation in regard to flight tests at these speeds is similar to that of a person who, though unable to swim, goes into the water at an unfamiliar beach which may have steep drop-offs and holes. Like the person on the beach, the pilot should explore conditions carefully, feeling his way along.

Experience has shown that at some Mach number above the critical Mach number of the wing, flight at higher Mach numbers may be either structurally unsafe or uncontrollable or both. Tests made in accordance with rule 2 permit an extrapolation of data obtained at lower Mach numbers and at various accelerations which will indicate the maximum Mach numbers and accelerations at which the airplane may be safely operated from either the structural or stability-and-control standpoint.

In applying this rule, a useful rule of thumb for estimating the critical Mach number of unswept wings is that the critical Mach number of low-drag airfoil sections at the design lift coefficient is 0.70 for sections 15 percent thick, and is higher by 0.01 for every percent the wing is thinner than 15 percent, and is lower by 0.01 for every percent the wing is thicker than 15 percent. Sweepback, of course, raises the critical values.

Experience indicates that for Mach numbers up to approximately 0.06 above the critical, increments of Mach number of 0.02 are sufficiently small for safety, although at higher Mach numbers, increments should not exceed 0.01 Mach number.

Even though rule 1 is observed, it is possible to have structural troubles due to buffeting. One purpose of rule 2 is to help avoid these troubles. To illustrate, figures 5, 6, and 7 show the limits of Mach number and load factor at which buffeting appeared on three airplanes during flight tests by the NACA. The data from which figure 5 is derived have been presented in references 2 and 3. These limits are called the buffet boundaries. It is noted in figures 5 and 7 that when the buffet boundary is exceeded structural failure may occur even though the allowable load factor is not exceeded. In the case of the airplanes for which data are presented in figures 5 and 7, buffeting or other compressibility effects, rather than inadequate design by the specifications used, were the causes of the structural failures. In maneuvers at lower altitudes structural failure did not occur on either airplane even though higher-than-allowable load factors were imposed.

Extensive operation of an airplane while it is buffeting is generally undesirable, and safe operation up to allowable load factors is generally possible, provided the buffet boundary is not exceeded. For these reasons the buffet boundary has been generally recognized as a limiting condition for safe operation, supplementing the boundaries otherwise limiting airplane operation. However, as shown in figures 5, 6, and 7, it is generally possible for the buffet boundary to be exceeded for limited periods without structural failure occurring. Therefore such a boundary is unduly conservative if used to define the limit accelerations for test purposes. A "tolerable limit of buffeting," based on a test pilot's opinion, is presented in these figures. There is, at present, no engineering method by means of which a safe tolerable limit of buffeting may be established. Reliance in regard to the establishment of a satisfactory tolerable limit of buffeting is almost entirely dependent upon the test pilot's experience and discretion. More detailed discussion with regard to buffeting and the establishment of a tolerable limit of buffeting will be taken up later, because this is an important factor in regard to the test pilot's willingness, as well as safety, in taking an airplane to high Mach numbers.

Considering rule 2 in regard to stability and control, it may be that above the critical Mach number of the wing compressibility effects on the wing or tail or both may make it impossible to maneuver the airplane much beyond the buffet boundary even though it is structurally safe to do so. This limitation is demonstrated by figures 8 and 9, taken from reference 4, which show elevator angle and elevator control-force characteristics of a fighter airplane. Figure 8 shows that beyond a Mach number of about 0.72 the elevator movement required to maneuver the airplane at a given acceleration increases markedly, and it points to the possibility that at some higher Mach number the amount of longitudinal control available from the elevator would be so limited that a pull-out from a dive could not be made. Figure 9 shows that at high subsonic Mach numbers the elevator control force required to maneuver may rise markedly, and that the control force per unit of acceleration may become so large that the pilot cannot pull out of a dive.

Even in level flight, some airplanes require up-elevator movement rather than down-elevator movement with further increase in Mach number beyond some high subsonic value. This characteristic is apparent to the pilot as a nosing-down tendency and is explained in reference 5. When such a condition exists, flight tests should be carried to higher Mach numbers only with great caution, for if the nosing-down tendency becomes worse as the Mach number of flight is increased, and if the tests are carried to a Mach number at which more than full-up elevator is required for straight flight, the airplane would be uncontrollable. Figures 10 and 11 are presented to show measurements of a nosing-down tendency at high subsonic Mach numbers as observed during test flights by the NACA of two fighter airplanes. In the case of figure 10 it will be observed that, although the elevator angle indicates the development of a nosing-down tendency at the higher Mach numbers, the elevator control force gives no indication of it. It is possible in this case that the nosing-down tendency might go unnoticed by a pilot until he is in difficulty, since his principal warning of this dangerous condition comes from the force on rather than from the position of the elevator control. However, in the general case, the nosing-down tendency is indicated by both elevator angle and elevator control force as illustrated in figure 11.

Figure 12 is presented to show a trend that model tests at very small scale by the wing-flow method indicate to be possible at high subsonic speeds. As may be seen from this figure, as Mach number is increased a nosing-down tendency of relatively mild degree may first develop, but this may be followed by nosing up, and then by an abrupt and large nosing down.

Another hazard, other than an uncontrollable dive, is possible as a result of the nosing-down tendency and the increase in stick-force gradient at high Mach numbers, particularly if the trim tab or adjustable stabilizer is not handled with discretion. This danger is demonstrated by study of figure 13, taken from reference 4, which shows the accelerations it was possible to attain for two values of elevator control force. In figure 13 it is seen that whereas at the highest Mach number (0.78) an acceleration factor of only 3 can be obtained with 50 pounds pull on the elevator control, the acceleration resulting from this force rapidly increases as the Mach number is decreased, an acceleration factor of about 10 resulting at a Mach number of about 0.68 if the 50-pound pull is maintained. This condition could lead to inadvertent stalling of the airplane. By the same token it is clear that, if at a Mach number of 0.78 the trimming device were adjusted to keep the airplane in level flight (an acceleration factor of one), a tremendous push would be required to keep the airplane from exceeding its limit load factor of 7.5 as the Mach number decreased. If the trimming device is relatively ineffective at the higher Mach numbers, the effect just described would be still worse.

Another factor to be considered is the change in stick-force gradient with acceleration even though the Mach number is constant. There have been cases of stick-force gradients changing with acceleration as shown by the upper curve in figure 14. When such a change occurs it is plain that inadvertent pitching up of the airplane is possible.

To summarize, by following rule 2 the buffet boundaries and longitudinal control may be judiciously explored. Data obtained in flight on buffeting may be plotted in the form shown in figures 5 to 7, and data on longitudinal control may be plotted in the forms shown in figures 8 to 14. From these plots, extrapolations can be made which will help to predict the characteristics at slightly higher Mach numbers. As flight tests progress the extrapolations can be continually revised, and a limit Mach number for tests from the standpoint of buffeting and longitudinal control can be estimated. However, as indicated by figure 12, extreme caution must be taken in making an extrapolation over too large a range of Mach number as the trends may reverse suddenly.

<u>Rule 3: There should be accurate recording and analysis of essential data as tests progress.</u>- This rule is a corollary of rule 2.

Data which must be recorded are: indicated airspeed, altitude, normal acceleration, and elevator angle. Many other items, such as elevator control force, may be profitably recorded. Obviously, recording of information is essential in tests of the kind discussed, since the pilot could not make adequate notes from indicating instruments.

The pilot's indicating instruments of Mach number, altitude, and acceleration should be properly calibrated and free of lag in order to avoid confusion in applying the conclusions from the recorded data. The danger of not having comparable recorded and indicated data should be apparent in test flying of such a nature that changes of Mach number as little as 0.01 may make the difference between safe and unsafe operating conditions.

Much has been written about the precautions necessary to avoid errors in flight measurements. This phase of instrumentation is not necessarily the province of the test pilot, but he would be prudent to understand the situation thoroughly.

THE HAZARD OF BUFFETING

As has been indicated earlier, although at high subsonic Mach numbers the buffet boundary is generally regarded as defining a limit for safe operation, it is generally possible for the buffet boundary to be exceeded somewhat, at least for limited periods, without structural failure resulting. This possibility is demonstrated by the data presented in figures 5, 6, and 7. It was pointed out, however, that there is no engineering method by which a safe tolerable limit of buffeting may be established, and therefore, at present, the determination of such a boundary is almost entirely in the hands of the test pilot.

Figures 6 and 7 show that, in order to demonstrate an airplane to the limits of Mach number at which safe flight is possible, some boundary defining the tolerable limit of buffeting is necessary, because limiting the performance of the airplane on the basis of the boundary at which buffeting starts is too conservative. For example, if the buffet boundary is not exceeded, it would not be possible for the airplane for which data are shown in figure 6 to recover from a dive at a Mach number higher than 0.764, since this is the Mach number at which buffeting occurs at a load factor of one. In the case of figure 7 the limit Mach number on this basis would be 0.794. With each airplane, however, these Mach numbers have been safely exceeded, as the test data show. Information that may aid the test pilot in establishing a tolerable limit of buffeting will now be presented and discussed.

Partial structural failure that has occurred during buffeting in two cases, provides information useful in establishing the tolerable limit of buffeting. On the basis of these failures and other experience of the author, the tolerable limit of buffeting is suggested in figures 5, 6, and 7.

Of course, the matter of buffeting is not quite as simple as it has been pictured thus far. Not only do fatigue characteristics of materials place an indeterminate limit on the length of time that operation with severe rapidly reversing stresses is safe, but the parts that may be affected by buffeting vary with the type of airplane and the conditions of operation. Buffeting may occur on wings, tail surfaces, controls, and other parts. Buffeting of one part may be more serious from the standpoint of structural failure than buffeting of some other part. The part that is most likely to fail first from buffeting will vary from airplane to airplane. Some comments on the effects of buffeting of various parts of the airplane may therefore be of value.

An impression of buffeting is sometimes given by flutter. In high-speed flight a type of flutter called transonic flutter has recently appeared. Transonic flutter may occur with only one degree of mechanical or structural freedom and appears to result from time delays which are due to near-sonic velocities in the air flow. Transonic flutter has occurred for short periods of time without causing structural failure, but it did cause partial failure of an aileron in at least one instance. With relatively rigid control systems having little backlash the amplitude of transonic flutter has generally been small; this type of flutter has therefore been referred to as "buzz." Adherence to the second part of rule 2 is important in exploring transonic flutter because, as is indicated in figure 15, transonic flutter may occur at lower Mach numbers as the lift coefficient is increased. The Mach number and frequency are functions of the characteristics of each airplane, so the limits shown in figure 15 are presented only for illustration. In some cases, the severity of the oscillations may become greater as the Mach number and lift coefficient are increased. Any sudden change in the floating angles of control surfaces as the Mach number is increased above the critical should be regarded as a warning that conditions for transonic flutter are being approached. This warning may not always appear, however, nor does it always indicate the imminence of transonic flutter.

Buffeting of the tail surfaces has caused structural failure, as noted for one example in figure 5 and reported in reference 3. Severe buffeting may result from tail surfaces being in the turbulent wake from the wing. Such a condition is likely to occur at Mach numbers above the critical of the wing and at high lift coefficients because of the spread and increased turbulence of the wing wake. It would be wise for the test pilot to pay particular attention to the extent of buffeting of the horizontal-tail surfaces when he exceeds the buffet boundary.

It is possible that at high Mach numbers the wing may shock stall unevenly, causing, in addition to buffeting, erratic and abrupt rolling motions. The amount of hazard from such a motion is not immediately apparent, but it creates decided apprehension in the pilot's mind. Rolling oscillations of this type, shown in figure 16, that occurred during a test flight of a fighter airplane by the NACA were sufficient to convince the test pilot of the inadvisability of proceeding to a higher Mach number. On some airplanes unsymmetrical shock or other factors cause yawing motions which are equally disagreeable.

Buffeting has also occurred because of canopies, and external stores such as fuel tanks or bombs. In the case of external stores the buffeting has resulted in failure of the mount and loss of the store.

LEVEL VERSUS DIVE TEST FLYING NEAR SONIC MACH NUMBERS

In view of the discussion thus far, some interesting points may be brought up in regard to the safety of test flying near sonic Mach numbers by diving as compared with the safety of such test flying when confined to level or nearly level flight.

In level flight, if difficulty is experienced, it is possible to return to lower Mach numbers fairly quickly by merely decreasing power. In a dive, to decrease speed, it is necessary to increase the lift coefficient unless suitable brakes are available. If buffeting is encountered in a dive, recovery generally involves increased buffeting as the lift is increased. As has been brought out in the earlier discussion, experience has shown that safe flight is possible with acceleration above that at which buffeting starts, and the tolerable limit of buffeting in figures 5, 6, and 7 falls off much more slowly with increasing Mach number than the boundary at which buffeting starts.

Obviously, a higher Mach number may be attained for a given amount of power if the airplane is dived rather than flown in level flight. Thus by making use of gravity rather than additional power, the weight and complication of an airplane while undergoing tests at a given Mach number may be less. The decreased weight allows higher factors of structural safety, and increased safety in take-off and landing. The elimination of some of the power plant otherwise required reduces troubles and hazards inherent in the use of all power plants, and may prevent use of untried means of augmenting thrust at the same time untried realms of sonic flight are being explored. Some of the power plants which might be used in airplanes in level flight at high Mach numbers are of such a nature as to make it difficult to follow precautionary rule 2. Rockets, for example, permit thrust to be varied only in large increments, that is, each rocket is either on or off.

It should be emphasized that, whether made in dives or level flight, initial tests near sonic Mach numbers should not be carried out below the minimum altitudes specified by rule 1. In dives the shallowest practicable angle should be used for each Mach number. In order to comply with these rules, dives must be started at high altitudes.

Certain safeguards have been developed which aid in dive flight testing. One of these is the dive-recovery flap. (See reference 6.) It appears, however, that at high subsonic Mach numbers, the effectiveness of the dive-recovery flap is considerably reduced if not entirely absent, and therefore the best safeguard would probably be a drag-producing device. A drag device which would instantly respond to the pilot's control and which would permit selective increments of drag to be imposed by the pilot so that he could slow the airplane down at the rate desired would be a great safety aid in dive flight tests. The maximum drag of such a device should preferably be of sufficient magnitude so that the airplane could be slowed down to a Mach number at which stability and control troubles would be absent while the airplane was still above the minimum altitude safe in accordance with rule 1.

Based on experience gained in test flying at high subsonic Mach numbers, largely by utilizing the diving technique and the foregoing analysis, it is the opinion of the author that test flying near sonic Mach numbers may be nearly as safe in dives as in straight flight, provided the precautionary rules given in this report are strictly followed.

PERSONAL PRECAUTIONS

There are other phases of high Mach number flying which, although common to many types of test flying, will be touched on briefly because of their importance. The value of snugly fitted safety belts and shoulder strips should constantly be remembered. Oxygen equipment must operate properly, and the pilot should always be aware of hazards and action to be taken in case of trouble. For flight above 45,000 feet, body pressure is necessary. Although many future high-speed airplanes may have pressure cabins, the use of a safety pressure suit (one not pressurized ordinarily, but capable of being pressurized with oxygen in an emergency) should be kept in mind, when and if such suits become available. The use of a "g" suit would increase the pilot's tolerance to acceleration, particularly when of long duration.

Best means of exit with parachute should be investigated, but often this is a futile matter, because regardless of method of exit the pilot getting out at high speed is liable to strike the tail of the airplane. Experimentation is now underway which may result in improvement of this situation. Opening of the chute should be delayed until below 20,000 feet altitude to permit slowing up before opening, and to get quickly to the region where auxiliary oxygen is not required. Much more could be written on the subject of personal precautions, but other literature is available and should be read.

CHECK LIST

Because of the many factors to be considered in test flying near sonic Mach numbers, it may be helpful to make use of a check list such as is presented in table I. Prior to flight, the figures called for in this table could be listed on the basis of the best information available at that time, and then as flight tests progress the figures could be continually revised on the basis of the data obtained.

CONCLUDING REMARKS

Three general precautionary rules for test flying near sonic Mach numbers are presented:

Rule 1. All initial flight tests near sonic Mach numbers should be carried out at an altitude at which excessive air loads cannot result even though the airplane is stalled.

Rule 2. At Mach numbers above the critical of the wing, flight tests at progressively higher values of Mach number should be undertaken only in small increments and only after exploring accelerated-flight characteristics at lower Mach numbers.

Rule 3. There should be accurate recording and analysis of essential data as tests progress.

The difficulties discussed may not occur in future airplanes, because continuous research and development may minimize or eliminate these undesirable traits. On the other hand, undesirable traits as yet unknown may be encountered in the Mach number range in which tests have not yet been made in flight, and therefore the precautions presented are advisable.

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3. Clousing, Lawrence A., and Turner, William N.: Flight Measurements of Horizontal Tail Loads on a Bell P-39N-1 Airplane (Army No. 42-18476) During Stalled Pull-Outs at High Speed. NACA RMR, Apr. 1944.

4. Turner, William N., Steffen, Paul J., and Clousing, Lawrence A.: Compressibility Effects on the Longitudinal Stability and Control of a Pursuit-Type Airplane as Measured in Flight. NACA ACR No. 5I13, 1945.

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6. Boddy, Lee E., and Williams, Walter C.: A Summary and Analysis of Data on Dive-Recovery Flaps. NACA RRM No. A7F09, 1947.

TABLE I.– HIGH MACH NUMBER FLIGHT TEST CHECK LIST

1. Based on Mach number and allowable load factor, the minimum altitude for flight tests is ____ feet.

2. The critical Mach number of the wing is______.

3. The Mach number at which buffeting starts at 1 "g" is ____ at an altitude of ____ feet.

4. The Mach number of the tolerable limit of buffeting in level flight is ____ at an altitude of ____ feet.

5. The Mach number at which the elevator angle or control force required for level flight changes abruptly with increase in Mach number is ____ at an altitude of ____ feet.

6. The Mach number and acceleration at which the elevator control-force gradient becomes dangerously small are____ and ____ g units at an altitude of ____ feet.

7. Flutter was noted at the following Mach numbers, altitudes, and accelerations:

Mach number __________
Altitude __________
Acceleration __________

8. Significant longitudinal, lateral, or directional oscillations or abrupt erratic motions occurred at a Mach number of ____ at an altitude of ____ feet.

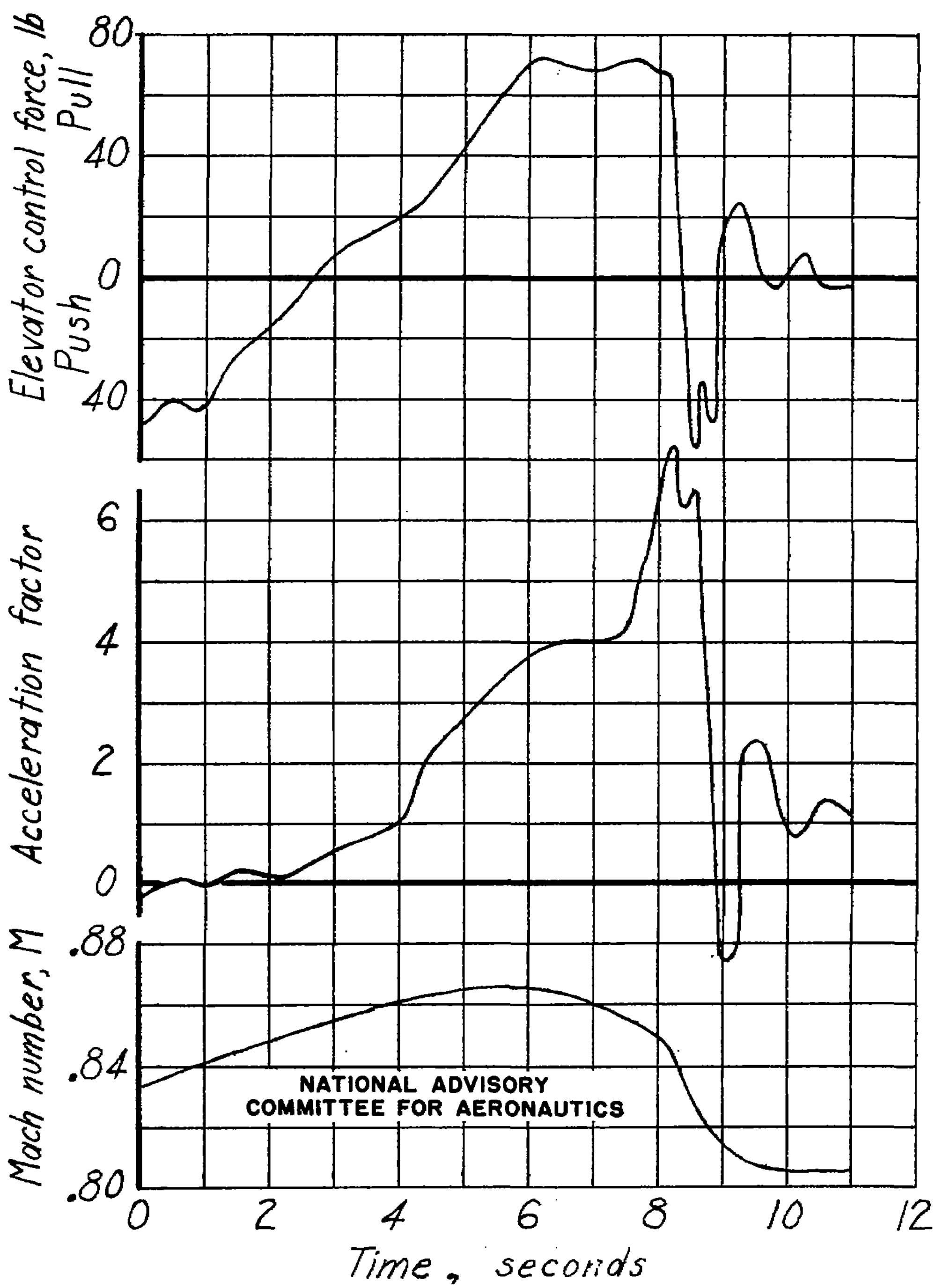

Figure 1.- Time history of an abrupt uncontrolled pitch-up during dive recovery with a fighter airplane at about 27,000 feet altitude.

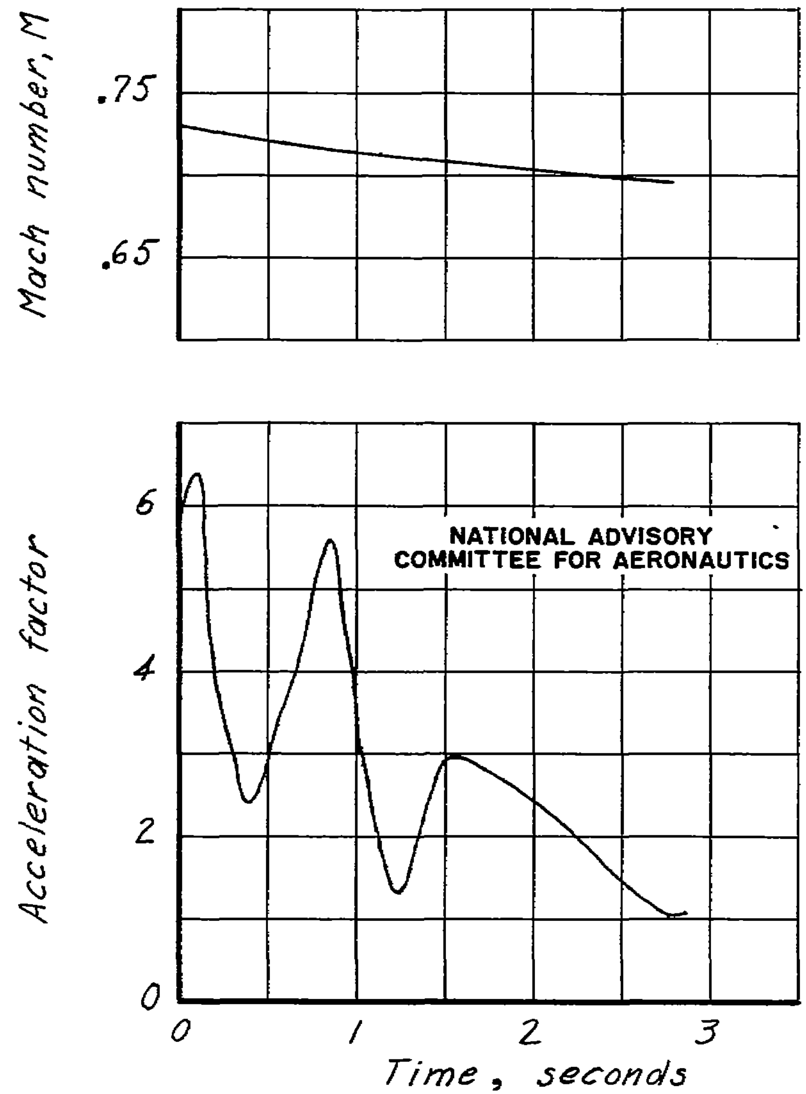

Figure 2.- Time history of an uncontrolled longitudinal oscillation which started while the airplane was in a steady dive.

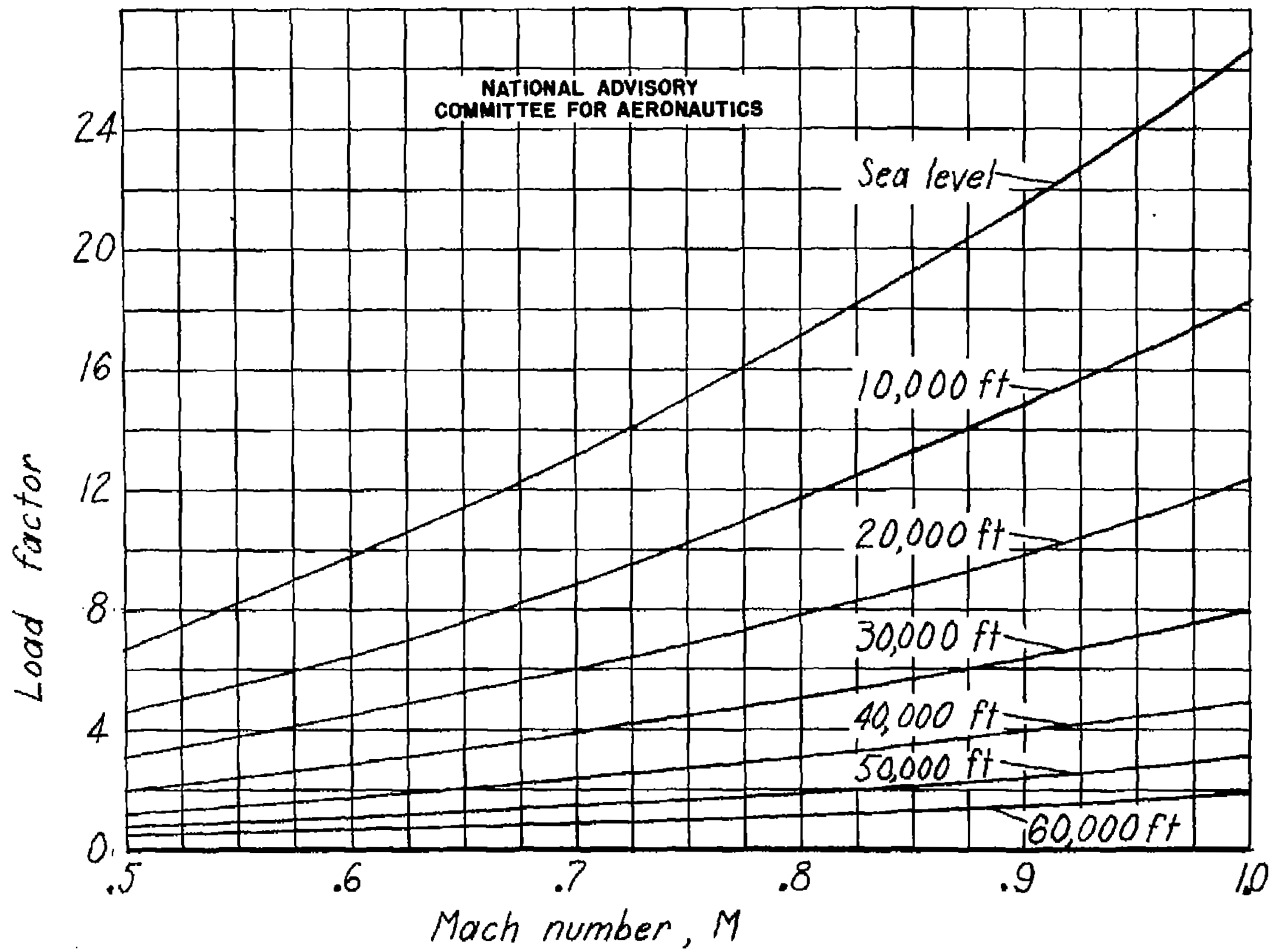

Figure 3.- Effect of altitude on maximum load factor possible with a wing loading of 50 lb/sq ft and the maximum lift coefficient shown in figure 4.

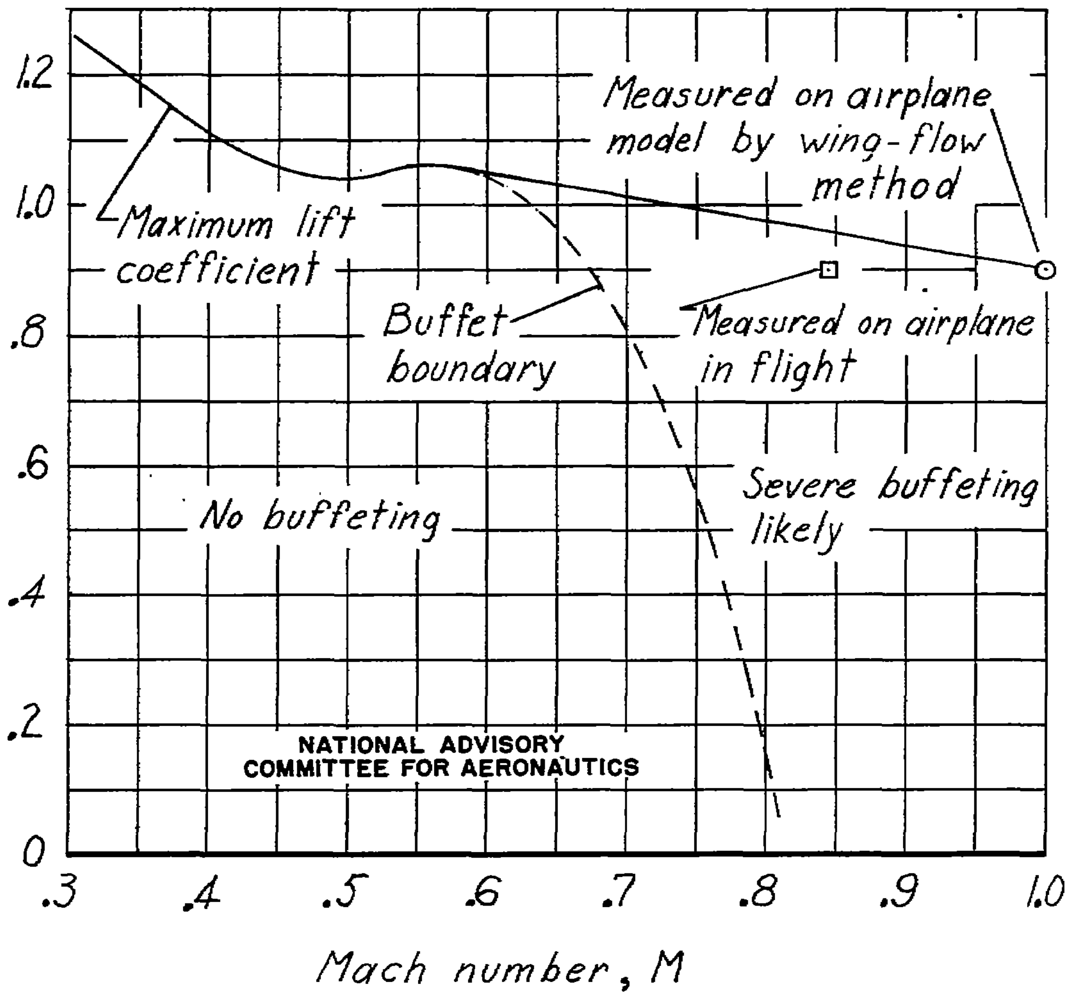

Figure 4.- Typical variation of maximum lift coefficient and buffet boundary with Mach number.

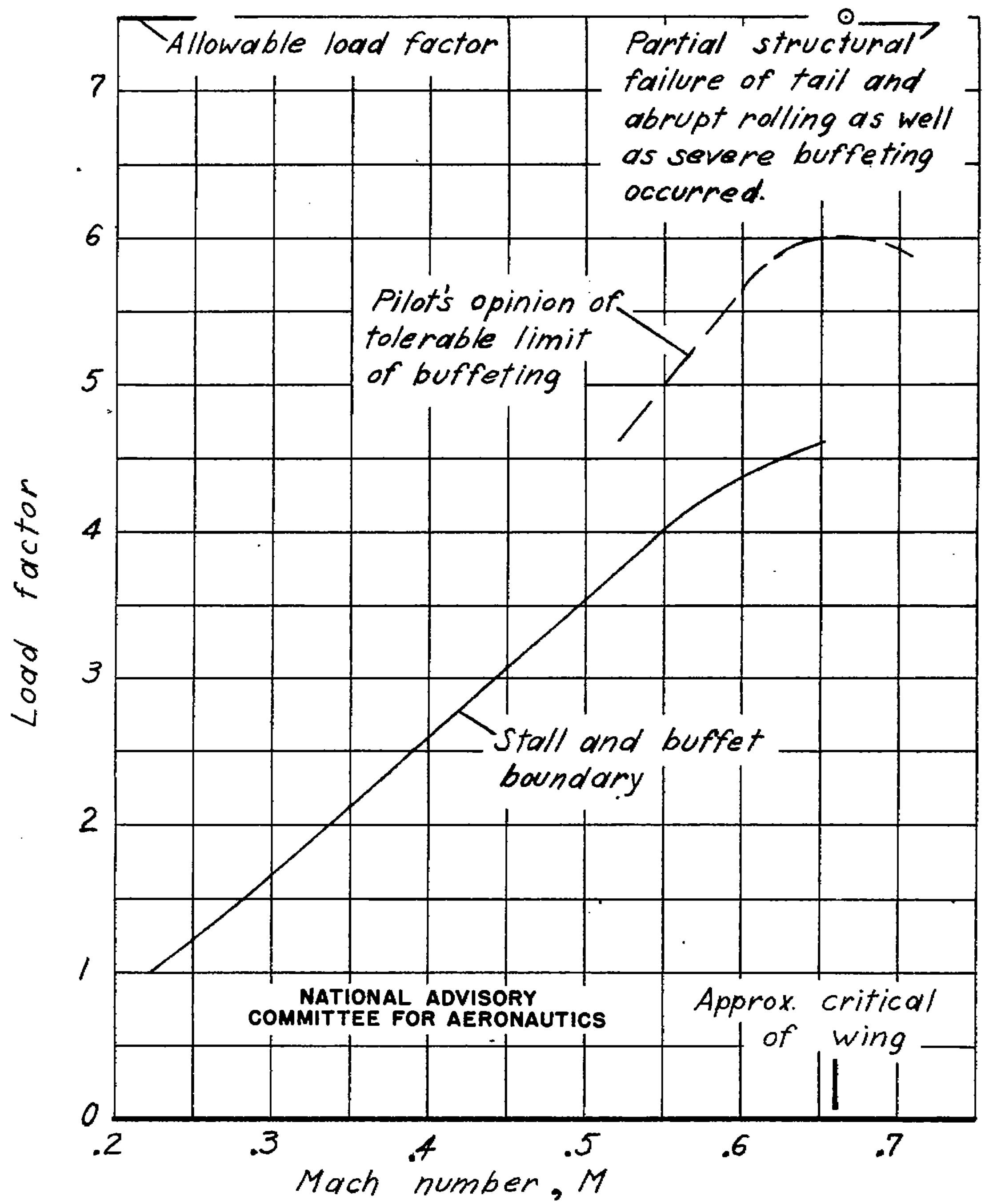

Figure 5.- Stall and buffet boundaries measured on a fighter airplane at about 25,000 feet altitude.

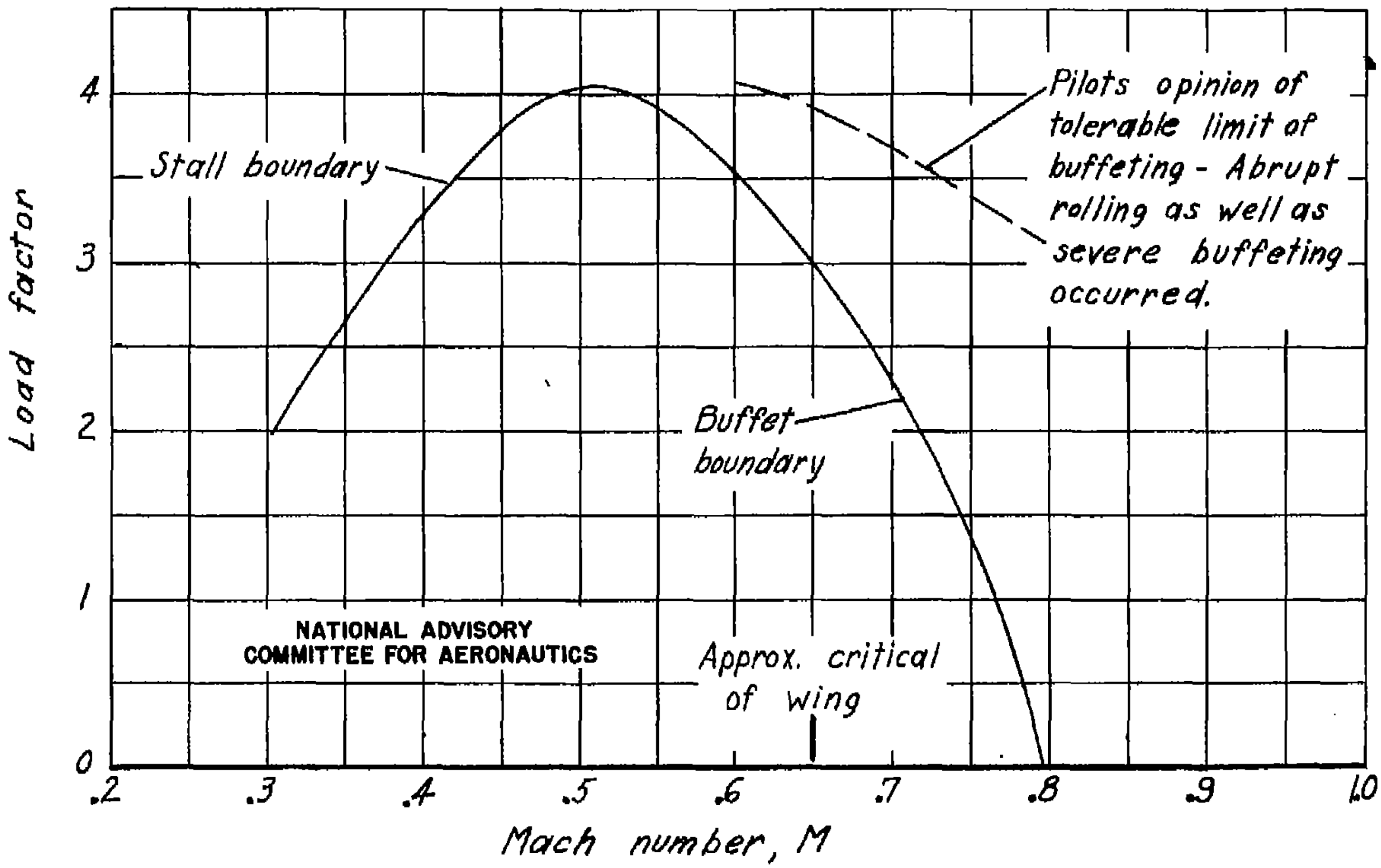

Figure 6.– Stall and buffet boundaries measured on a fighter airplane at about 20,000 feet altitude.

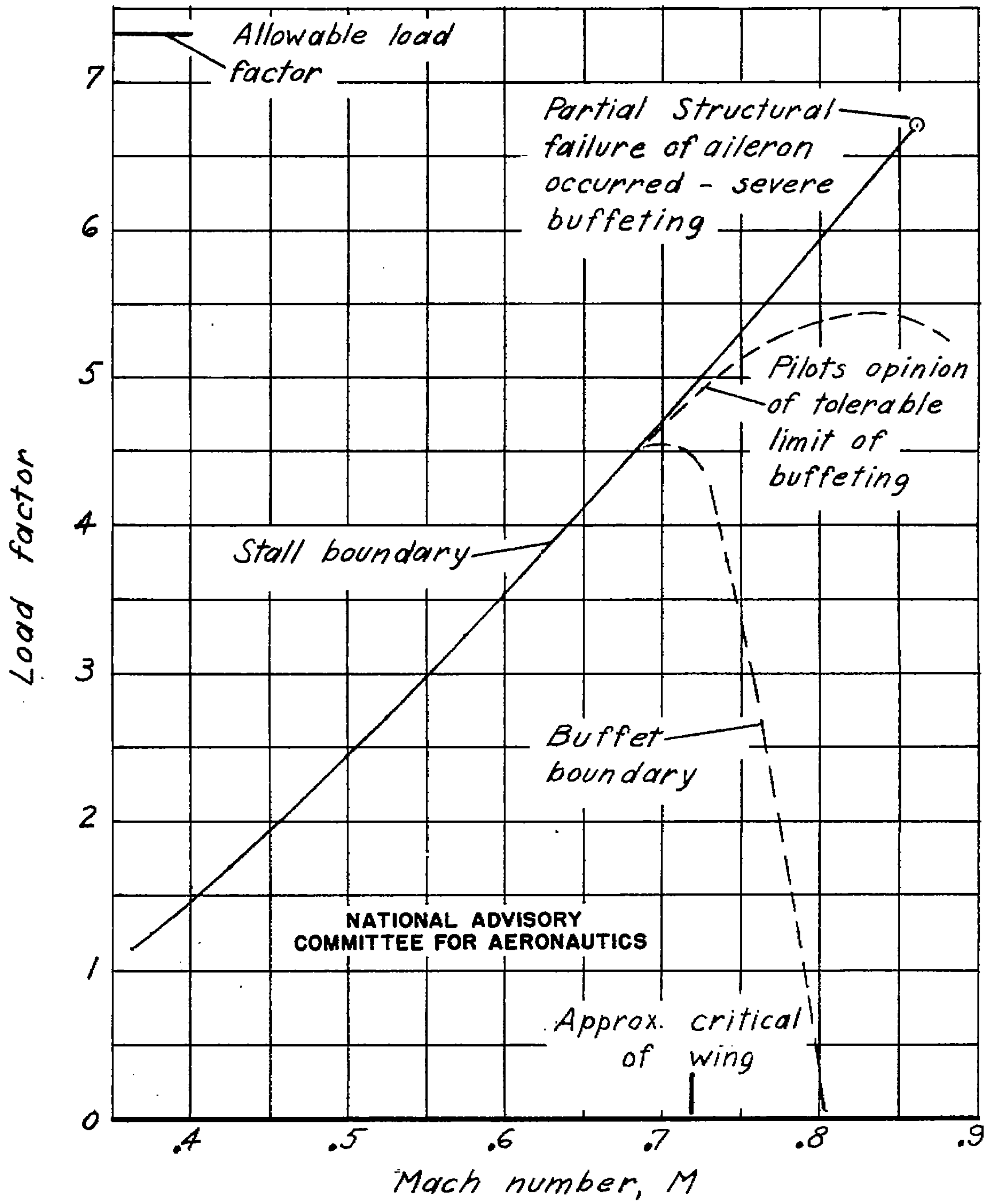

Figure 7.- Stall and buffet boundaries measured on a fighter airplane at about 30,000 feet altitude.

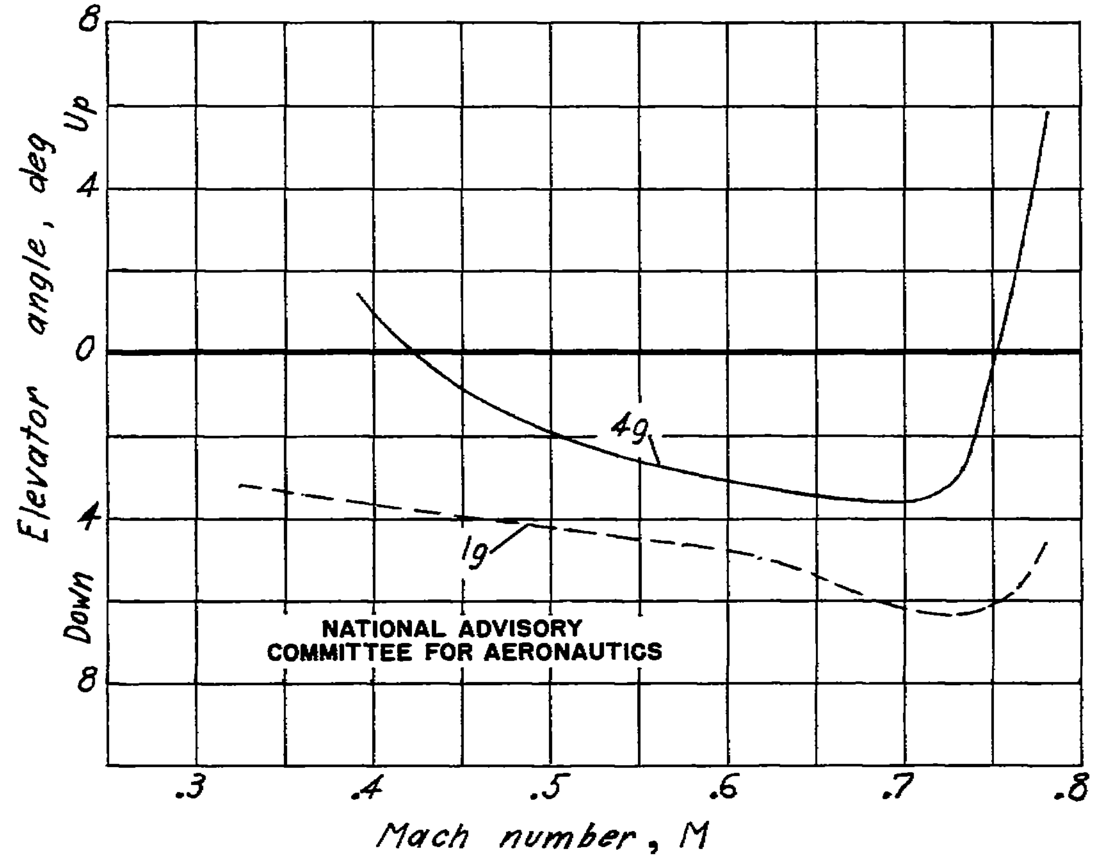

Figure 8.- Elevator angle for a fighter airplane at various Mach numbers and 20,000 feet altitude.

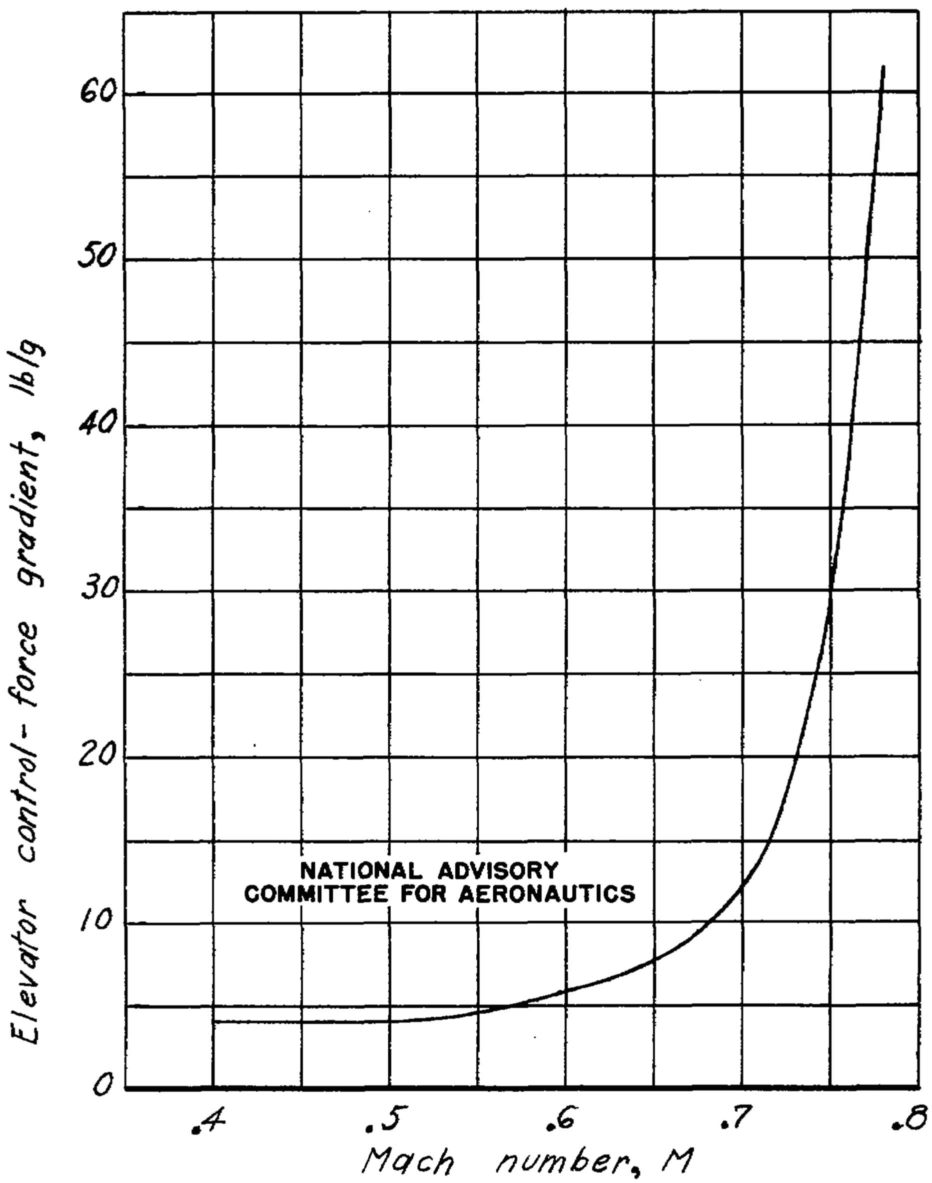

Figure 9.- Variation of elevator control-force gradient with Mach number for a fighter airplane at 15,000 feet altitude.

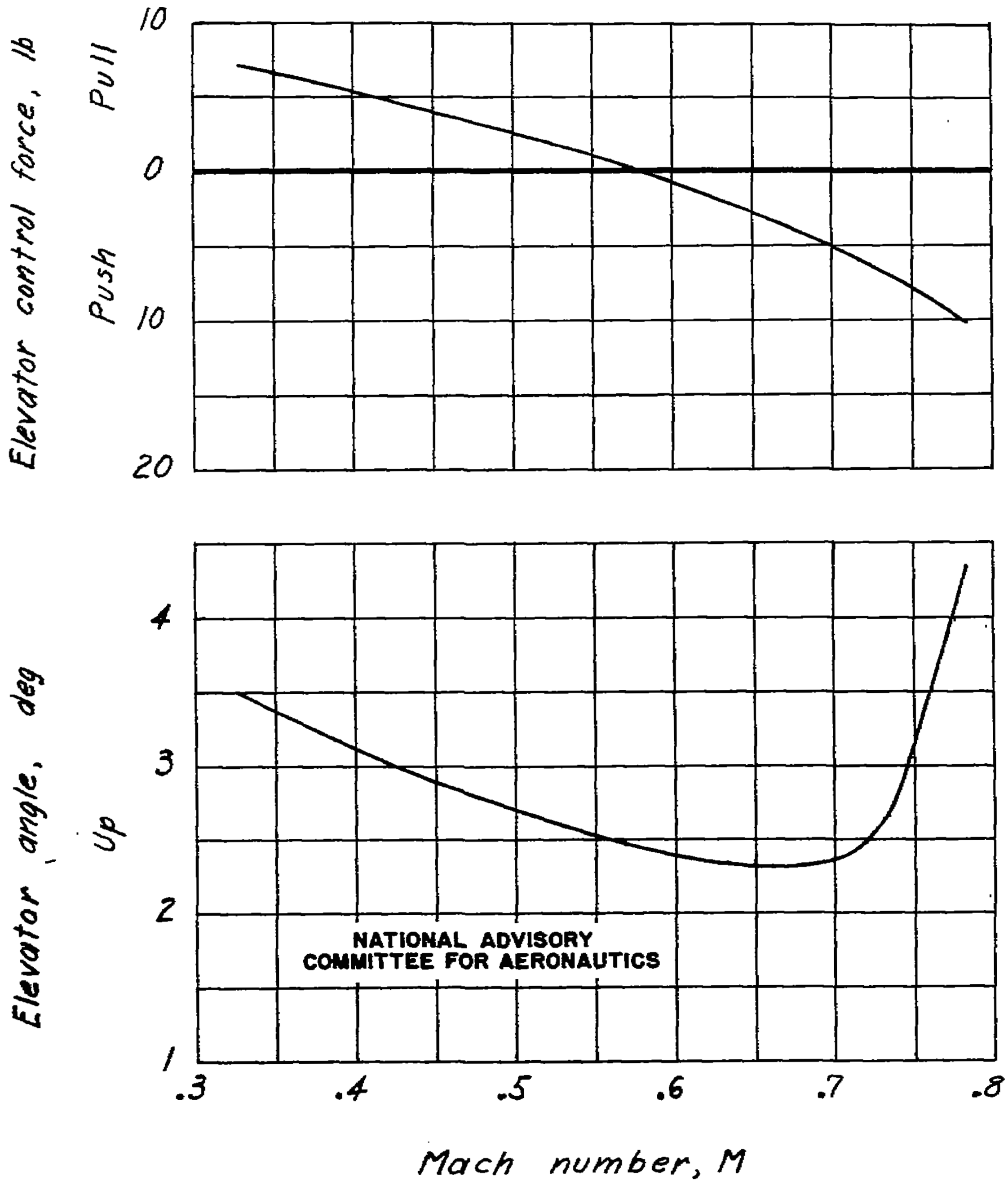

Figure 10.- Nosing-down tendency of a fighter airplane at about 22,000 feet altitude indicated by elevator angle but not by elevator control force.

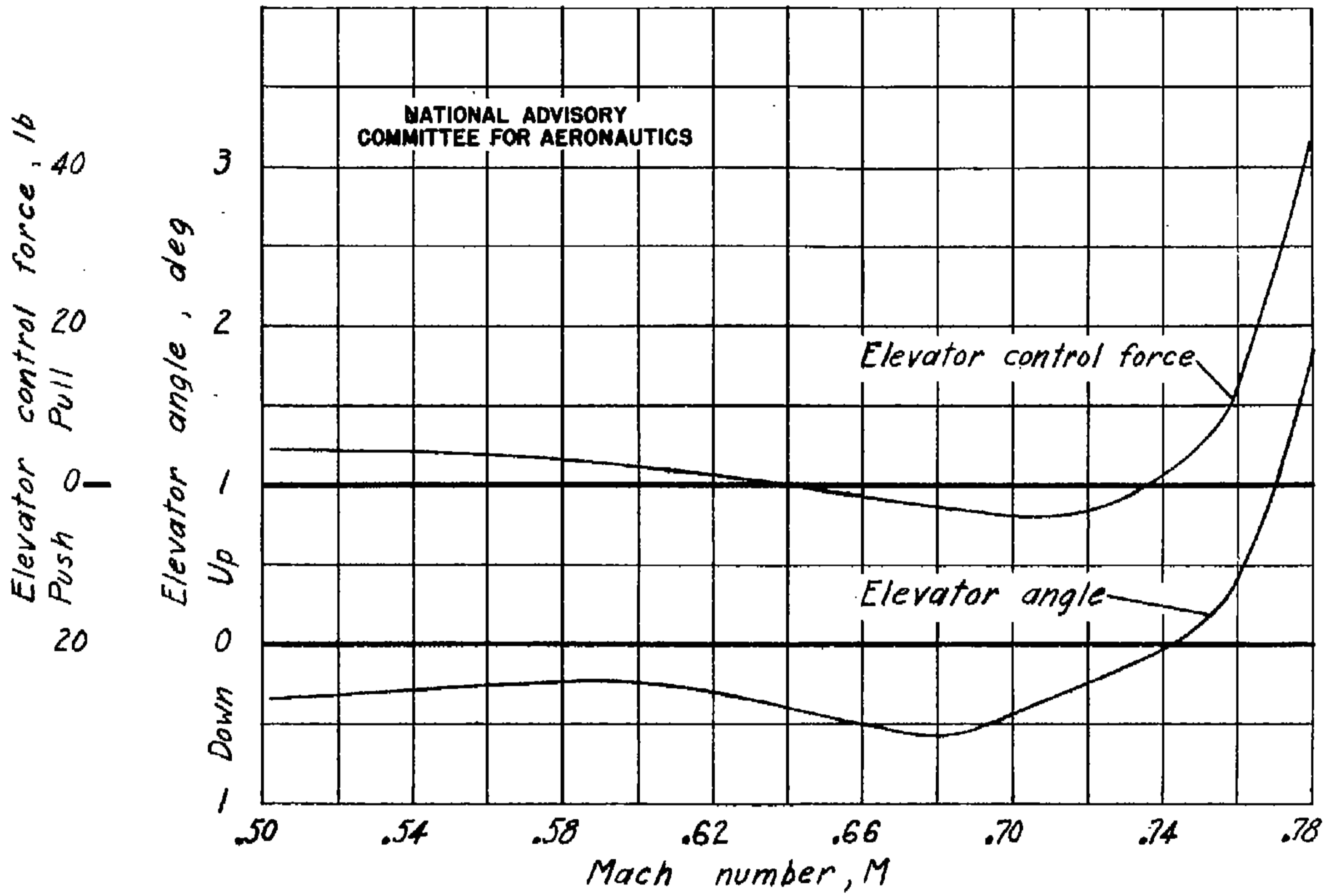

Figure 11.- Elevator angle and control force required by a fighter airplane at about 20,000 feet altitude.

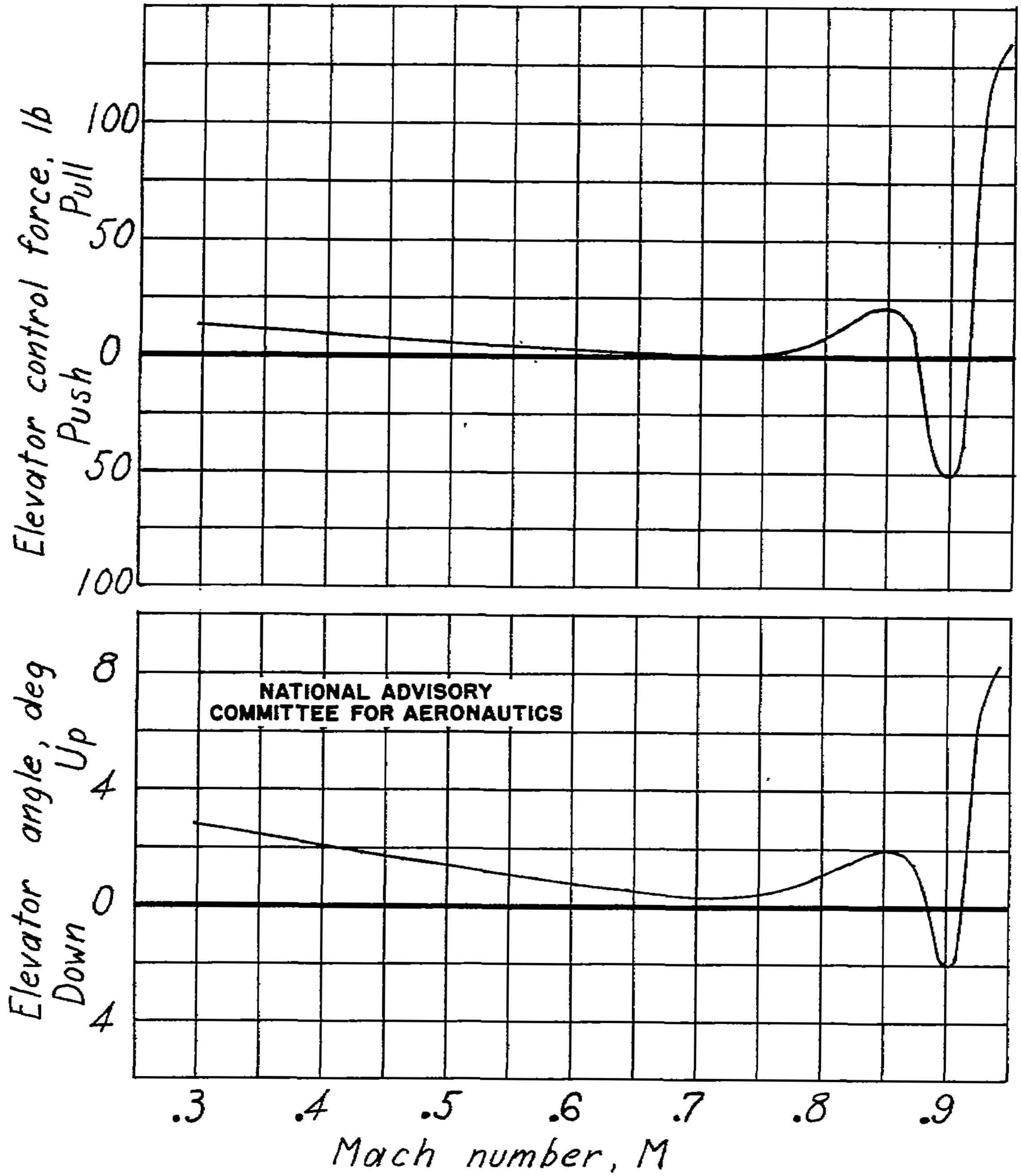

Figure 12.- Longitudinal trim at transonic speeds from wing-flow tests of an airplane model.

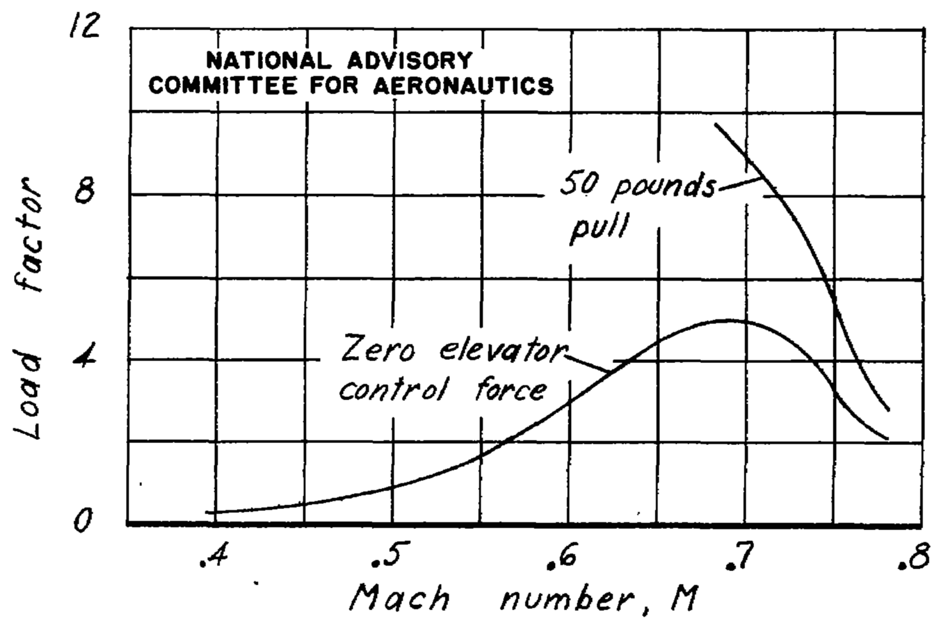

Figure 13.- Variation of acceleration with Mach number for two values of elevator control force for a fighter airplane.

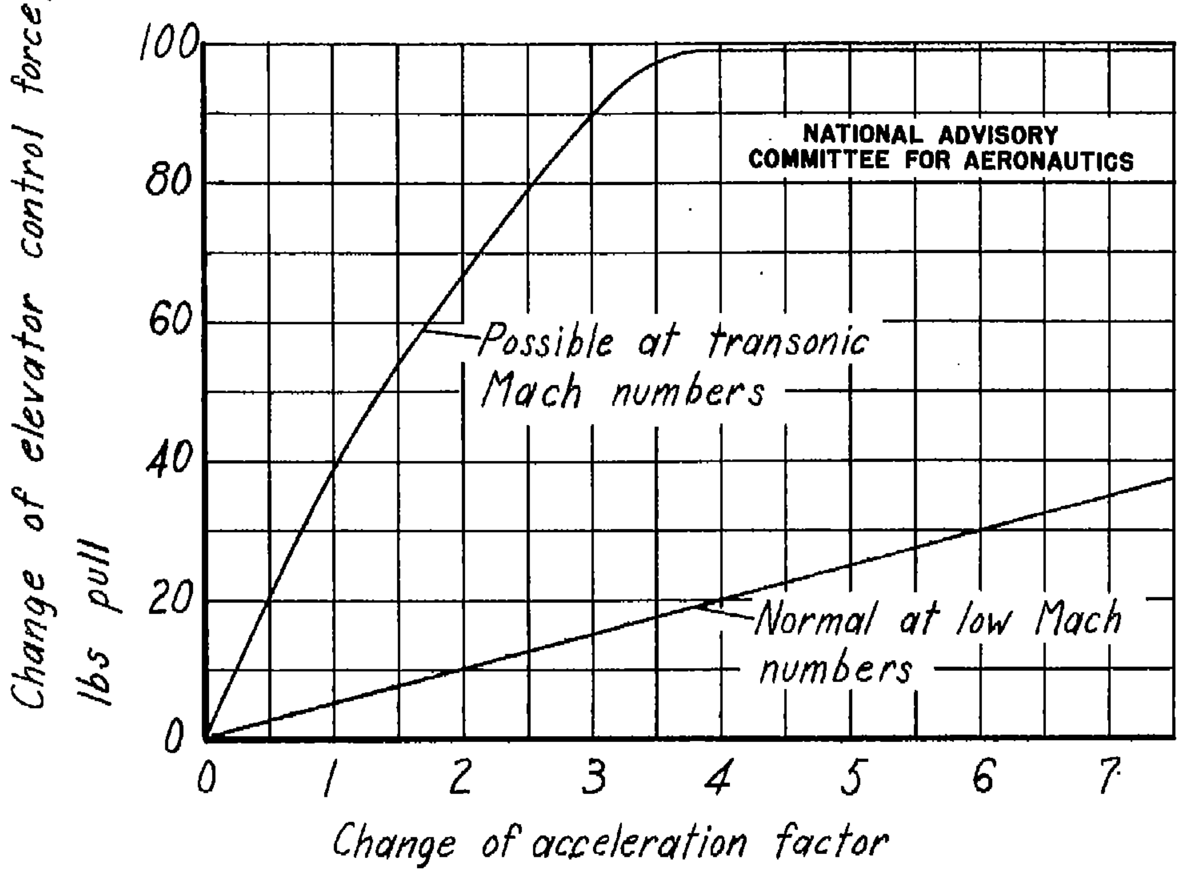

Figure 14.- Possible stick-force gradients at transonic speeds.

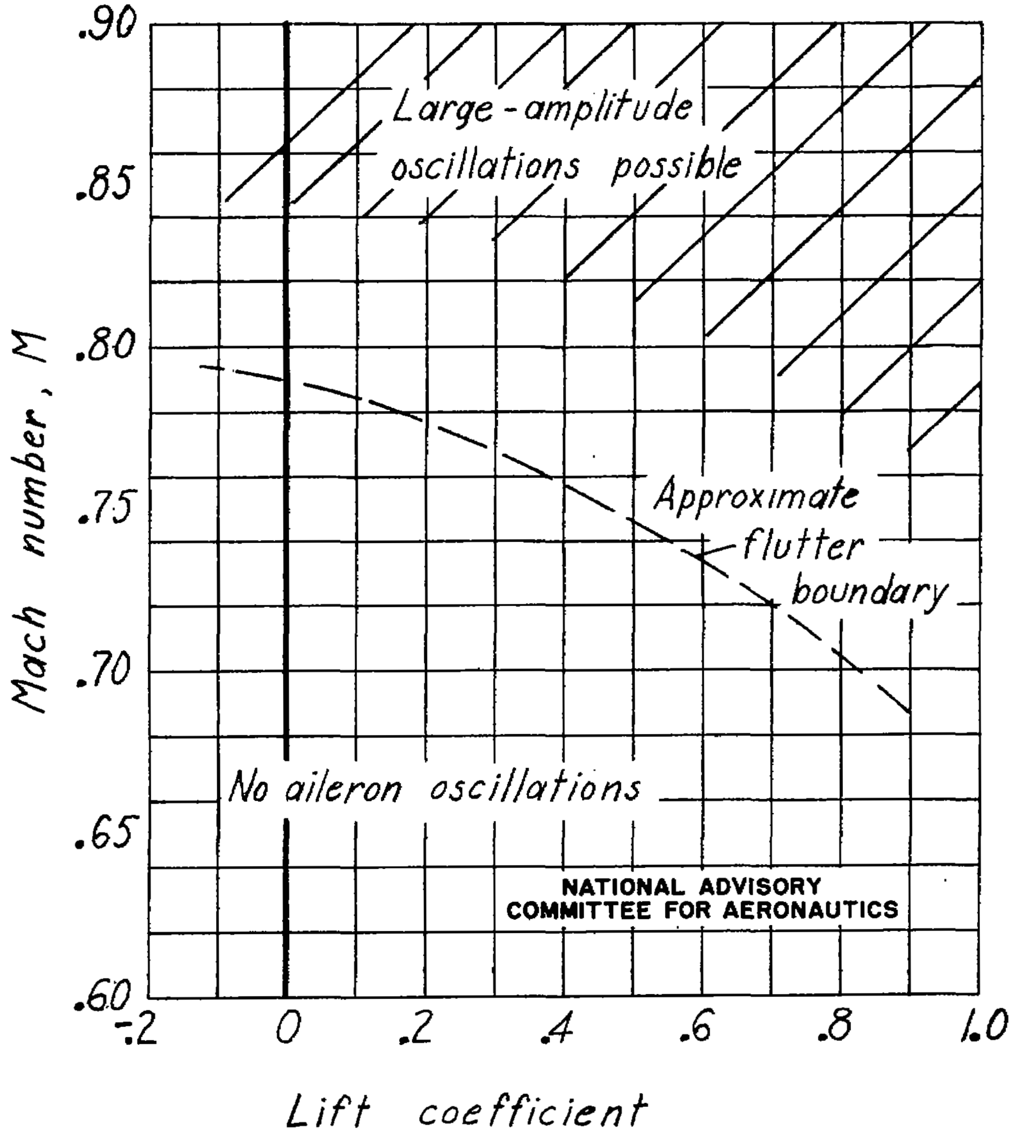

Figure 15.- Illustrative variation of transonic flutter boundary with Mach number and lift coefficient.

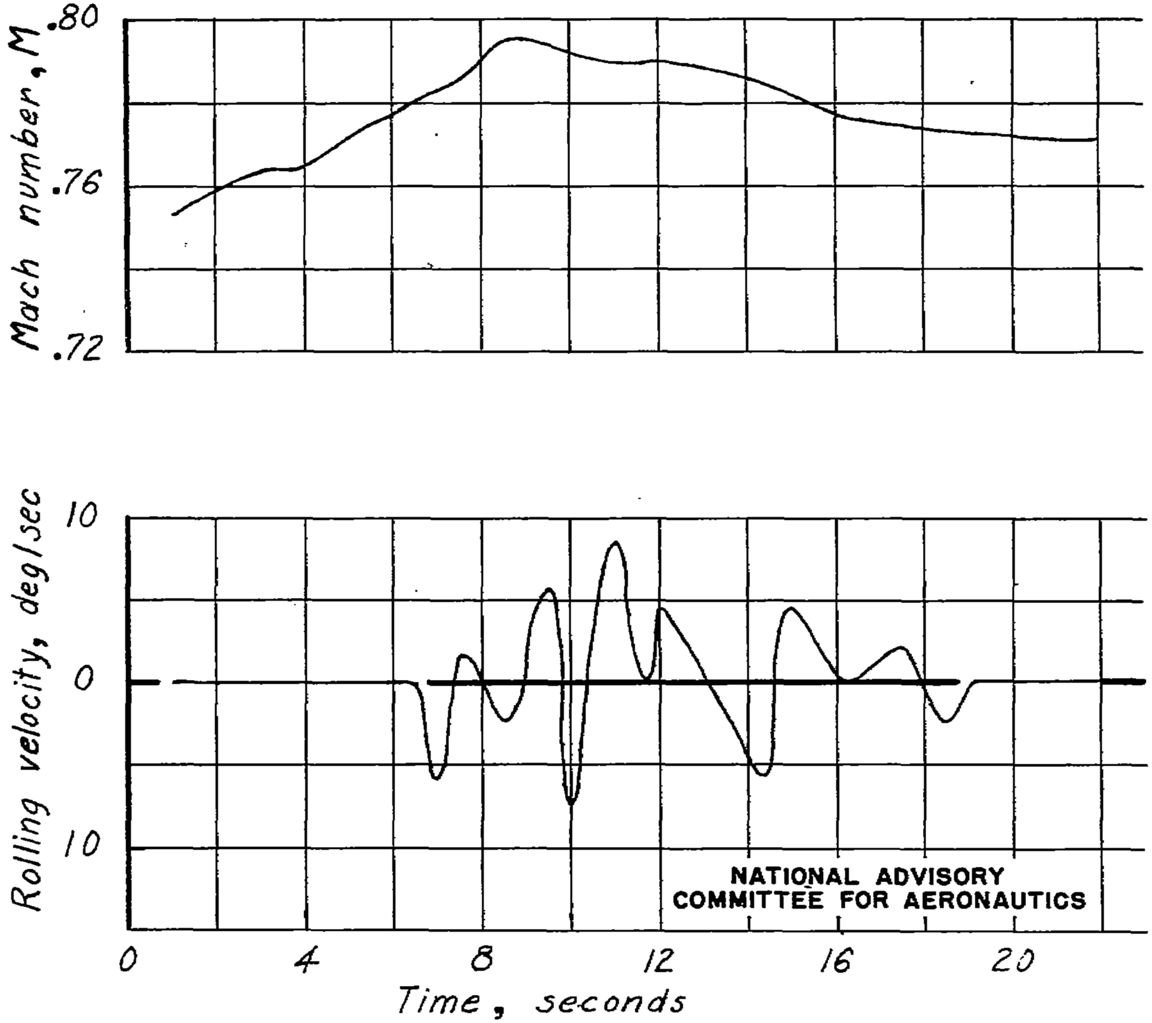

Figure 16.- Severe uncontrolled lateral oscillations measured in flight with a fighter airplane.